# Paper 0010

# Results from the testing of a heavy duty diesel engine with hydrogen fumigation

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## Abstract

$CO_2$ emissions from road freight currently account for one third of emissions from the transport sector. The high load factors and journey energy requirements mean measures such as downsizing and electrification which have been successfully applied to passenger vehicles are less effective on freight vehicles. The substitution of part of the diesel fuel with a low or zero carbon fuel offers a route for reducing the emissions. Hydrogen is an attractive, flexible fuel which can be manufactured from low carbon electricity. In this paper, we describe a programme of research in which up to 50% (by energy) of the diesel fuel was substituted with hydrogen, introduced as a homogenous mixture to the inlet manifold. The test engine was a heavy duty single cylinder engine with high pressure (3000 bar) fuel injection capability calibrated to Euro VI emissions levels. Two calibrations were identified with and without EGR, both achieving Euro VI emissions levels with post combustion $NO_x$ control. The various hydrogen supply options are discussed including bulk manufacture and a novel on board approach using steam reformation with integral waste heat recovery. The results showed a significant proportion of the diesel fuel can be substituted with hydrogen without compromising the brake thermal efficiency of the engine or $NO_x$ emissions significantly, introducing the potential for a flexible, dual fuelled solution using conventional heavy duty engine architecture.

## 1   INTRODUCTION

In 2007 the transport sector was responsible for 23.5% of the $CO_2$ production (figure 1) of which commercial vehicles were responsible for roughly one third. Light duty applications are able to use well known measures such as electrification to reduce the carbon emissions and impact on urban air quality. However as the vehicle power, range and duty requirements increase, these solutions become increasing difficult to realise technically and commercially. The compression ignition Diesel engine is likely to remain the dominant powertrain in these sectors for the foreseeable future [1]. The challenge is therefore is to find methods to reduce the $CO_2$ impact of these vehicles whilst maintaining low emissions and commercial viability.
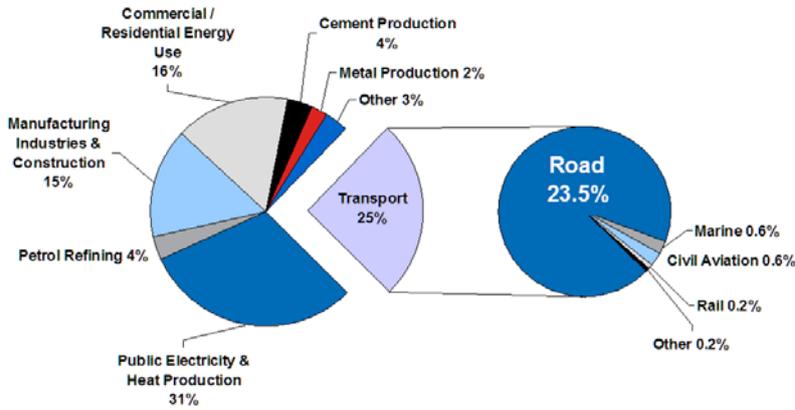


**Figure 1: $CO_2$ emission from (a) all sectors and (b) transport**

A range of measures have been proposed for reducing commercial vehicle carbon emissions, including switching to a zero carbon fuel such as a biofuel, improvements in the powertrain efficiency and waste heat recovery [2]. Fuel substitution with hydrogen has been considered by others but distribution, on board storage and the efficiency of the hydrogen engine remain challenging [3]. In this paper, we consider the potential for the partial substitution of up to 50% of the diesel fuel (by energy) with hydrogen. Two related pathways for the supply of hydrogen are considered:

1. Hydrogen produced off board of the vehicle and supplied to the vehicle as a fuel stored in a high pressure canister.
2. Hydrogen produced on board - as a hydrogen rich reformate from on board reforming of the diesel fuel.

For either strategy to be viable, it is essential that hydrogen can be efficiently burnt within legislative emissions levels in the dual fuelled engine. In this paper, a programme of research will be described which aimed to assess the potential of diesel – hydrogen combustion in a commercial vehicle sized single cylinder engine operating at Euro VI emissions levels assuming exhaust aftertreatment. The two proposed hydrogen delivery pathways will first be described. The experimental programme and results will then be presented, focusing on strategies to achieve the target Euro VI heavy duty emission levels. The paper concludes with a discussion of the potential of the diesel-hydrogen engine, in the context of the experimental results and potential hydrogen supply pathways.

## 1.1 Hydrogen – diesel combustion

Hydrogen and diesel combustion studies to date have focused on two strategies. In the first strategy a homogenous mixture of hydrogen is compressed and a small diesel pilot injection is introduced to ignite the hydrogen with the diesel contributing little to the overall heat release [4]. The second strategy, the subject of the research reported in this paper, involves a more balanced mixture of diesel and hydrogen with the hydrogen typically contributing up to 50% of the chemical energy. Again the hydrogen is introduced into the inlet system and compressed forming a homogenous mixture into which the diesel charge is injected. Hydrogen – diesel combustion might be expected to increase the rate of heat release due to the rapid combustion of the hydrogen component, reducing heat losses to the chamber wall and increasing thermal efficiency [5]. However, this has not been the case in many experimental studies. The closest research to the present study was performed at the University of West Virginia on a Euro III Cummins and later a Euro IV Mack engine with cooled EGR. Hydrogen quantities of up to 8% by volume of the inlet air were used. Hydrogen combustion efficiencies as low as 68% [6] were reported, significantly less than that for diesel, resulting in hydrogen slip and a reduction in the overall brake thermal efficiency (BTE) accounting for both the diesel and hydrogen fuels. Up to a 3% reduction in BTE was reported with the combustion efficiency improving above the lower flammability limit (LFL) [7] when the hydrogen-air mixture could support a flame. The amount of hydrogen slip was load dependent, being greatest at light load conditions. Hydrogen slip has also been reported by other researchers on light duty engines [8].

Liew [9] reported emissions measurements across the 13 mode ESC for diesel – hydrogen combustion. The $NO_2$ to NO ratio was observed to increase significantly when hydrogen was added to the engine. At mid and high load conditions the addition of up to 3% hydrogen by charge air volume had little impact on $NO_x$ emissions but at higher concentrations the rate of heat release increased and a corresponding increase in $NO_x$ was observed. However Liu [6] reported a reduction in $NO_x$ at high hydrogen concentrations. Liu concluded the unburnt hydrogen affected the chemistry of the $NO_2$ and NO formation mechanisms favouring the formation of $NO_2$. Other researchers [8] have reported similar hydrogen concentration dependent relationships with $NO_x$ emissions.

Considering other emissions, there is a consensus view that the addition of hydrogen reduces HC, CO and particulate emissions. Morgan [10] proposed a three mode conceptual model to describe the ignition and combustion processes inside the hydrogen – diesel engine. The model was used as an aid to understanding the effect of hydrogen concentration above and below the LFL and in cylinder temperature, above and below the autoignition temperature of the two fuels.

## 2 HYDROGEN DELIVERY PATHWAYS

The three potential pathways for the supply of hydrogen to the engine are shown in figure 2. Bulk production of hydrogen by the steam reforming of methane or electrolysis of water could provide hydrogen as a separate fuel. An alternative method considered is the reforming of the liquid diesel fuel on the vehicle to produce hydrogen rich reformate, providing the option of the recovery of waste heat to power the reformer. In this way waste heat is effectively converted to chemical energy. This section describes the three delivery pathways in more detail.

## 2.1 Off-board hydrogen production

The hydrogen supply chain is currently dominated by two production pathways: steam reformation of a hydrocarbon and electrolysis. Whilst these two pathways account for close to all the hydrogen produced, reformation is currently the larger component accounting for 95% of production. This is driven by the comparative cost of electricity verses cost of the stock hydrocarbon e.g. natural gas which is the assumed feedstock in this paper. For both off-board pathways, the produced hydrogen must be pressurised to facilitate compact on-board storage. A US Department of Energy study [11] reported that if the hydrogen were produced at 20 bar and stored at 350 bar then additional compression work of 0.15 kWh/$kg_{H2}$ is required.
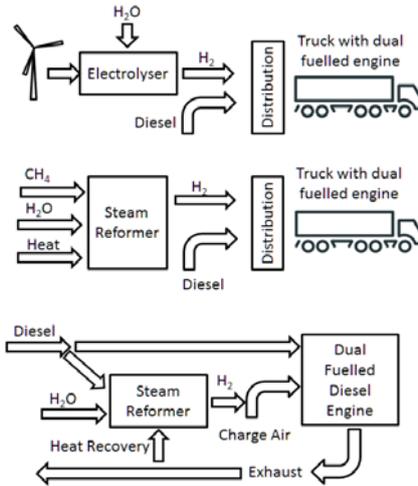
**Figure 2: Pathways for the supply of hydrogen through (a) of board electrolysis (b) of board reforming, (c) on board production**

## 2.2    Electrolysis

The basic cold electrolysis process is up 20% efficient. Recent developments have utilized higher temperatures and pressures and have increased the efficiency to the 50% to 80% range [12]. At this higher efficiency, production of 1 kg of hydrogen would require 50–79 kWh of electricity.  Assuming the internal combustion engine can burn hydrogen at a similar efficiency to diesel, then 358 g of hydrogen is required to displace 1 kg of diesel. If we assume 80% efficient electrolysis process, then 21.9 kWh of electricity is required to generate the 358 g of hydrogen. UK Government figures [13] report that current grid $CO_2$ intensity as 0.59 $kg_{CO_2}$/kWh when distribution losses are included.  Producing 358 g of Hydrogen using the UK grid would therefore generate 12 kg of $CO_2$. Given that the 1 kg of diesel displaced by the hydrogen would only produce 2.6 $kg_{CO_2}$ the merit of this approach is debateable unless the grid mix can be de-carbonised by a factor of 5 or where hydrogen is produced using wrong time energy (such as excess overnight wind generation) which would otherwise not be used.  Considering research on large scale grid balancing [14], this scenario is likely in the future where intermittent renewable generation contributes significantly to the generating mix.

## 2.3    Steam reformation

A large component of the hydrocarbon feedstock used to produce hydrogen is methane. In this paper this fuel used as a proxy to investigate this route for production.   The steam reformation reaction is as follows:

$CH_4 + 2H_2O \rightarrow 3H_2 + CO_2$
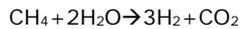
To produce 358 g of hydrogen, 955 g of methane is required and 2,600 g of $CO_2$ will be produced. Thus the system would be inherently marginally more $CO_2$ intensive than burning the equivalent quantity of diesel. This position is exacerbated when one includes the compression work and addition thermal energy to produce the steam.
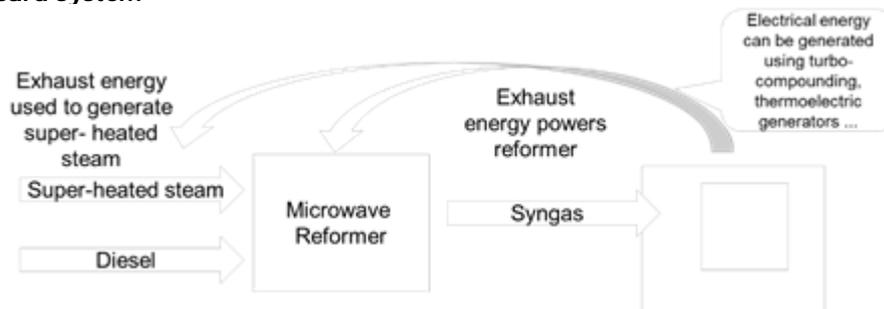
## 2.4    On-board system



**Figure 3: Schematic of on board steam reforming process**

Referring to figure 3, reforming the diesel on-board the vehicle using energy recovered from the exhaust to create superheated steam and microwave energy can produce a 25% increase in the calorific value of the fuel. This syngas, consisting typically of 70% hydrogen, 25% CO and the balance hydrocarbons and $CO_2$ is used to displace a percentage of the diesel. Simulation which assumed the combustion performance of the reformate – diesel

engine was the same as the diesel baseline indicates this approach could lead to an up to a 5% reduction in fuel consumption. This value is very competitive with other waste heat recovery and fuel consumption reduction solutions [2]. Recovered waste energy from the engine is used to drive the process and is effectively 'captured' in the syngas as an increase in the calorific energy over the diesel. This increase largely comes from the combustion of hydrogen produced in the decomposition of the water during the steam reforming process.

## 2.5    Summary

Table 1 summarises the $CO_2$ emissions from the various hydrogen delivery pathways discussed, compared to the diesel fuel baseline. Considering first the supply of hydrogen as a fuel from bulk manufacture, steam reformation of methane yields no overall benefit in $CO_2$. The $CO_2$ emissions generated during the manufacture of hydrogen through electrolysis is dependent on the efficiency of the electrolysis process and the carbon intensity of the electricity used for the process. At the current UK grid generating mix this option is unviable. However, this approach may be more attractive in the future because of the expected reductions in the carbon intensity of the grid through the displacement of fossil fuel generation with renewable and nuclear energy. In addition, the manufacture of hydrogen using surplus renewable energy also offers an attractive route for the balancing of the grid. The use of hydrogen manufactured in this manner could reduce carbon emissions from the commercial vehicle sector through the displacement of fossil fuels with a zero carbon fuel. The on board fuel reformation pathway is an attractive way of recovering waste heat and improving the overall fuel conversion efficiency of the engine running on diesel or similar fuels. However, to be viable the combustion efficiency of the dual fuelled engine must be comparable with current engines operating on diesel and additionally should not compromise the toxic emission levels of the engine.

**Table 1: Summary of carbon emissions from various hydrogen delivery options**

|  | Assumption | $CO_2$ per kg diesel equivalent |
|---|---|---|
| Diesel (baseline) | 1kg diesel | 2.6 kg |
| Hydrogen (electrolysis) | Current UK grid, 80% efficient optimised electrolysis | 12 kg |
| Hydrogen (electrolysis) | Zero carbon electricity available | 0 kg |
| Hydrogen (reforming) | Methane feedstock | 2.6 kg |
| Hydrogen (on board fuel reformation) | 5% improvement in powertrain efficiency through waste heat recovery | 2.47 kg |

## 3   EXPERIMENTAL PROGRAMME

### 3.1    Test Facility

The test programme was undertaken on a Ricardo Proteus single cylinder heavy duty installed at the University of Brighton. The engine was equipped with the Delphi F2E FIE capable of 3000 bar injection pressures. The engine configuration is summarised in table 2.

**Table 2: Engine Characteristics**

| Bore | 131.1 mm |
|---|---|
| Stroke | 150 mm |
| Compression ratio | 16:1 |
| Swept volume | 2 l |
| Swirl | Quiescent |
| Combustion chamber | Open Chamber |
| Diesel injection system | Delphi F2E Unit Injector |

Hydrogen was introduced upstream of the inlet manifold on a bend to ensure good mixing. The flow rate of hydrogen was controlled using a Horiba SEC Z552MGX mass flow controller. Air flow into the engine was supplied via a compressor. A series of nozzles were installed in the inlet system which were operated in a choked condition. The air flow into the engine could then be regulated by controlling the pressure upstream of the nozzles, isolating the air flow control and measurement from the high pressure fluctuations generated in the inlet system by the single cylinder engine. By this method the air flow into the engine could be set and held constant as hydrogen was introduced into the inlet system downstream of the nozzles. The engine and facility are more completely described in [10, 15].

## 3.2 Test Program

The test programme was designed to evaluate the impact of hydrogen fumigation and the viability of achieving Euro VI emissions with hydrogen-diesel co-combustion. Testing was concentrated at a mid-speed (1250 rpm) and load condition (196 Nm, 12 bar BMEP), equivalent to the A50 point on the ESC drive cycle. This condition is representative of a motorway cruise condition and therefore a representative key point for assessing the cycle fuel consumption impact under real world driving conditions. The hydrogen concentration was varied from 0% by charge air volume (diesel only) to the onset of either 'knock', or excessive rise in cylinder pressure due to early ignition of the hydrogen. In the case of tests with EGR, hydrogen concentrations were restricted to about 5% by volume (based on the air flow excluding the EGR) to minimise the risk of ignition in the inlet system initiated from particulate matter carried in the EGR.

The basic engine calibration was based on a previous extensive optimisation programme undertaken on diesel at various EGR rates and injection pressures [15]. Two engine calibrations were targeted:
- No EGR, with retarded injection timing and high efficiency (>95%) SCR for $NO_x$ control
- Light (20%) EGR, with advanced injection timing and 90-95% SCR for $NO_x$ control

Both these strategies have been applied by engine manufactures in the commercial vehicle sector at Euro VI. The rail pressure was held constant at 2000 bar and the air fuel ratio for the diesel only case at 25:1. The air flow was then held constant during the hydrogen swing. The effective air fuel ratio would therefore increase, as hydrogen displaces diesel fuel (at constant load) but the oxygen available for combustion would remain constant. For test conditions with EGR, a constant EGR rate of 20% was maintained. The back pressure on the engine was adjusted to 1.1 times the inlet manifold pressure to simulate the required pressure gradient to drive EGR through the short route and energy to drive the turbocharger.

Results were post processed and corrected for ambient conditions, as described in [10]. Particular attention was made in the calculation of the brake specific emissions with the introduction of hydrogen. Normally, air flow measurements on the single cylinder engine are derived from the air-fuel ratio measurement and fuel consumption measurements. With hydrogen fumigation, this is no longer possible and so air flow was measured and controlled using the critical flow nozzles.

## 4 TEST RESULTS

### 4.1 No EGR Case

The injection timing was set to 4° after top dead centre (ATDC), which represents 10° of retard from the timing for best efficiency, phasing the start of combustion to top dead centre. For the diesel only case (figure 4), the engine out $NO_x$ emissions were 7.8 g/kWh, requiring a $NO_x$ conversion efficiency of 95% to achieve Euro VI (0.4 g/kWh) vehicle out emissions. Referring to figure 4, $NO_x$ emissions are observed to climb to 4% hydrogen concentration and then level off before falling. This trend has been observed by others [6] and was attributed to the hydrogen initially increasing the rate of combustion and then, at higher concentrations reducing OH radicals which slow the $NO_x$ formation process. It is also possible the fall in $NO_x$ is due to the reduction in the quantity of diesel injected, reducing the size of the $NO_x$ formation zone in the diffusion flame. Further work is required to understand the $NO_x$ formation process in this type of engine.

The peak $NO_x$ emissions of approximately 10g/kWh would require an SCR conversion efficiency of 96%, which is viable but would require a substantial and well optimised SCR system and high consumption of Adblue with limited margin for degradation of the catalyst in service.

The BTE was observed to fall from the peak value of 39% for diesel only to 38.5% with 8.8% hydrogen concentration (by volume). At this concentration, the rate of cylinder pressure rise increases significantly and no further hydrogen was added to prevent damage to the engine. This change in BTE is within the experimental accuracy of the facility (+/-2%) but is systematic and so cannot be ignored. Again this trend has been observed by other researchers and was attributed to incomplete combustion of the homogenous mixture of hydrogen resulting in hydrogen slip. Below 4% hydrogen concentration, the air-hydrogen mixture cannot sustain a flame as the mixture is below the LFL and so any hydrogen that does not mix with the diesel flame will not burn and will pass through to the exhaust system. For example, hydrogen trapped in the crevice volumes and outer areas of the squish region will not mix with the diesel flame so the hydrogen content of these areas will not burn. Above 4% concentration, the air-hydrogen mixture will burn and so combustion would be expected to be more complete in these cases. This is apparent from the experimental results, but again a firm conclusion cannot be reached due to the small change in BTE and experimental uncertainty. Direct measurement of hydrogen in the exhaust was not possible with the equipment available but hydrogen slip is considered the most likely explanation for the observed drop in BTE.

Referring to figure 5, the 5%, 50% and 95% burn angles were determined from the cylinder pressure measurements and heat release analysis. It can be seen that up to 4% hydrogen concentration the 5% burn angle (indicative of the start of combustion) is unchanged showing no pre-ignition of hydrogen due to the concentration being below the LFL. The 5% burn angle is observed to advance above the LFL, indicating ignition of the hydrogen mixture prior to ignition of the main diesel charge. Below 8.8% concentration, the initial rate of rise of the cylinder pressure is modest indicating that the hydrogen is burning in a controlled manner rather consistent with a HCCI type of combustion mode, before uncontrolled ignition and a high rate of cylinder pressure rise 'knocking' type of combustion at higher concentrations (>8.8%.). At 8% hydrogen concentration, the diesel injection quantity was reduced by 50% and so the energy contribution of the two fuels is roughly equal.

The 50% burn angle is observed to progressively advance with the introduction of more hydrogen to the charge air. This is due to the shorter injection duration as diesel is substituted for hydrogen, and increase in the rate of combustion. The more rapid rate of combustion is consistent with the increase in $NO_x$ emissions observed up to 4% concentration. The duration of the combustion event (indicated by the 95% burn angle) is significantly reduced as more hydrogen is added beyond 4% hydrogen concentration. It is interesting to note the rate of combustion is observed to continue increasing beyond 4% but the $NO_x$ emissions flatten off and then fall. This could indicate a change in the chemistry of the $NO_x$ formation process, supporting the findings of previous researchers.
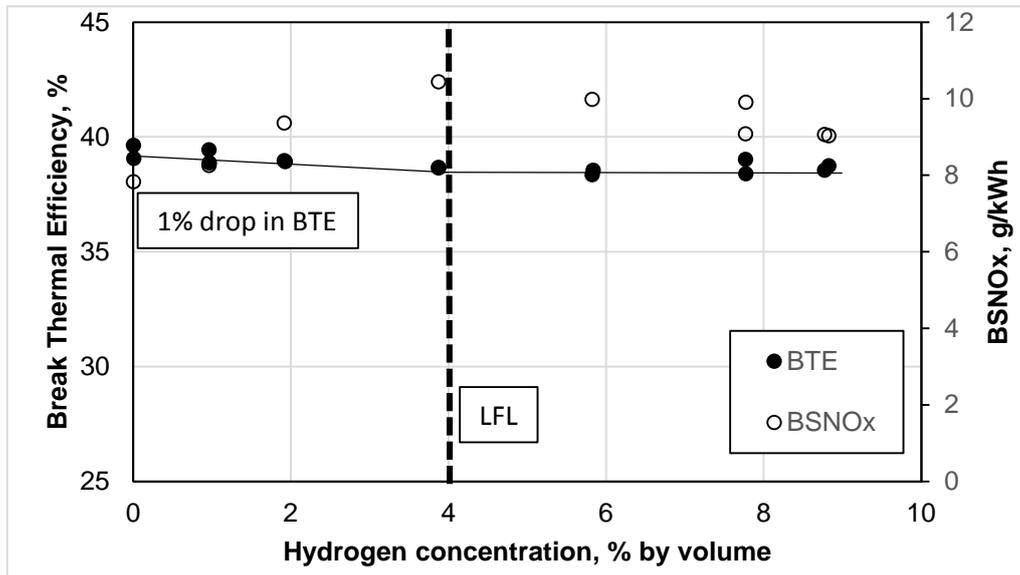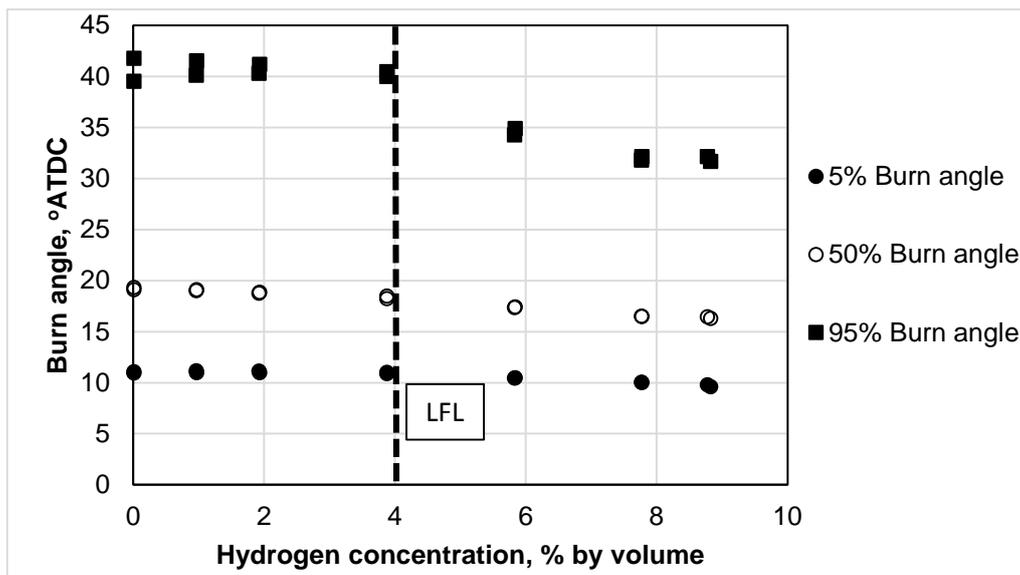


**Figure 4: BTE and BSNOx for no EGR case**



**Figure 5: 5%, 50% and 95% burn angles for no EGR case**

### 4.2  EGR Case

The addition of 20% EGR to the inlet manifold reduced the $NO_x$ emissions significantly, as expected (figure 6). In this case, the injection timing could be advanced significantly to -6° ATDC whilst maintaining engine out $NO_x$ emissions below 8 g/kWh. This advance in injection timing resulted in a three percentage point improvement in brake thermal efficiency at the diesel only condition relative to the no EGR case. The maximum hydrogen concentration achieved was 5.2%, slightly above the estimated effective LFL taking to account the EGR dilution effect of 5%. A similar reduction in BTE of 1% was observed to the no EGR case again probably due to incomplete combustion of hydrogen that does not mix with the diesel fuel and consequently slips through the combustion chamber. Analysis of the cylinder pressure traces (figure 7) showed almost no advance of the 50% and 95% burn angle with the addition of hydrogen. This is similar to the no EGR case (figure 5) as little advance in the 50% and 95% burn angles was observed until the hydrogen concentration exceeded the LFL. This level of EGR is therefore still effective in limiting the rate of heat release rise even in the presence of hydrogen.
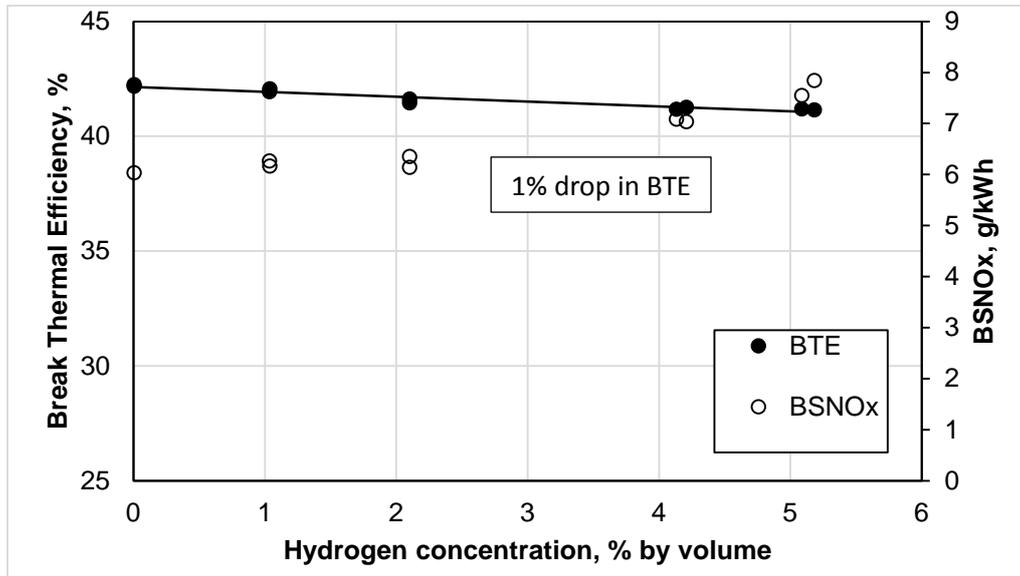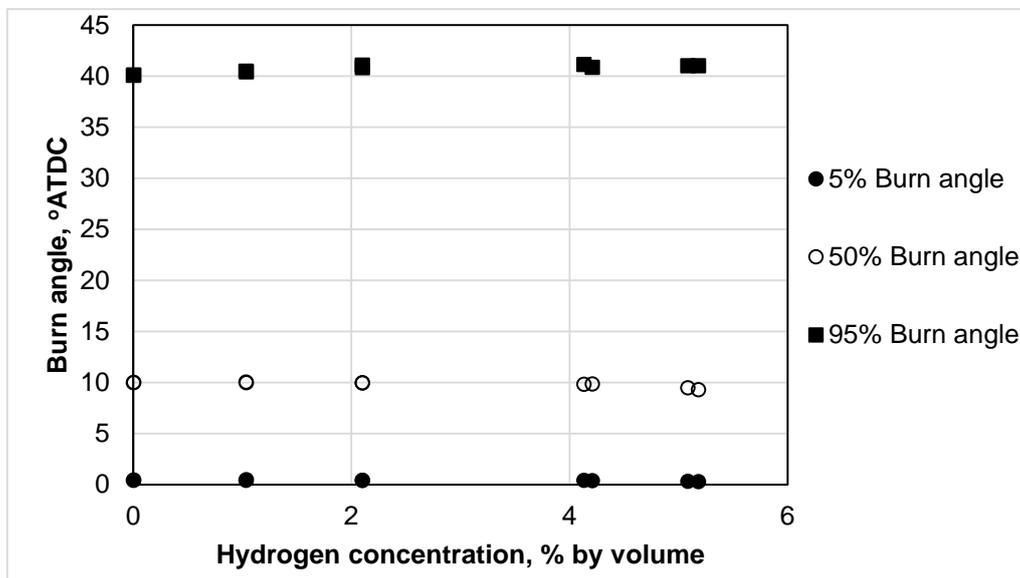
**Figure 6: BTE and BSNOx for 20% EGR case**



**Figure 7: 5%, 50% and 95% burn angles for 20% EGR case**

## 5    DISCUSSION

### 5.1    Engine Test Results

In both the EGR and non EGR cases an increase in $NO_x$ emissions was observed with the addition of hydrogen, of the order 20% compared to the diesel only case, peaking around 4-5% hydrogen concentration close to the LFL (4%).  This trend is consistent with other researchers and can be attributed to an in increase in the diffusion flame temperature as a consequence of the combustion of increasing quantities of hydrogen.  In the no EGR case, the $NO_x$ emissions were then observed to fall at higher concentrations of hydrogen.  The exact mechanism for this trend is unclear, but other researchers have attributed the fall in $NO_x$ to changes in the chemical kinetics of the $NO_x$ formation mechanism.  Significant shifts in the $NO_2$-$NO_x$ ratios have been reported [6] and the reduction of OH radicals by free hydrogen has been proposed as the mechanism for the observed $NO_x$ reduction.  It is also possible that the fall in $NO_x$ is simply due to a reduction in the size of the diffusion flame area as less diesel is injected. The present research is consistent with both these observations but direct verification through optical diagnostics is required to verify either hypothesis.

The drop in BTE observed is also consistent with other researchers and is attributed to incomplete combustion of hydrogen.  The observed drop (~1%) is generally lower than other researcher's findings.  The combustion system used for the current research is well optimised and produces very low levels of particulate emissions, indicating good air utilisation.  This, combined with the high diesel injection pressure (2000 bar) may result in better mixing of the air-hydrogen mixture with the diesel flame reducing the quantity of unburnt hydrogen.  Further research

is required to verify this hypothesis but it is clear from the present research that a well optimised combustion system for diesel also works well with a diesel – hydrogen mixture.

The engine test data shows both calibration strategies (with and without EGR) are viable and can achieve Euro VI emissions levels with $NO_x$ control aftertreament. The EGR strategy gave the most encouraging results as the timing could be advanced improving the BTE of the engine at $NO_x$ levels consistent with a modest sized SCR aftertreatment system. The no EGR solution is however viable but significant injection retard is required to maintain engine out $NO_x$ levels low enough to be practical with an efficient SCR system. The EGR strategy is therefore preferred, achieving both high thermal efficiency and low $NO_x$. From the testing to date, significant quantities of diesel fuel can be displaced without a significant BTE or $NO_x$ penalty. The combustion system has not been fully optimised and increasing the swirl level to improve air/hydrogen – diesel fuel mixing may reduce the BTE penalty further. Testing at other, particularly higher load conditions is also required, however other researchers have shown the hydrogen-diesel combustion performance tends to improve at higher loads and so similar or better results would be expected at higher load.

## 5.2 Implications for integration of hydrogen with a Heavy Duty engine

The test results indicate between 25 and 50% of the diesel fuel can be displaced with hydrogen without a significant $NO_x$ or BTE penalty. 25% substitution is attractive as at this level the inlet conditions are below the LFL removing the risk of ignition in the inlet system. Higher levels may be viable, with careful management of the ignition risk in the inlet system such as close coupling of the hydrogen injector to the inlet ports.

Considering the various hydrogen delivery pathways, in the near term the use of centrally manufactured steam reformed or hydrogen manufactured using grid electricity would not deliver a $CO_2$ benefit. The on board steam reformation pathway will however improve the overall system efficiency through the recovery of waste heat. Up to 15% improvement fuel energy was calculated through reformation process described in section 2, which would deliver up to a 5% improvement in overall BTE given the reduction in combustion efficiency observed during the current research. Longer term, the use of centrally manufactured hydrogen through electrolysis using 'wrong time' or low carbon electricity is attractive and would deliver significant reduction in $CO_2$ emissions without significant changes to the engine architecture or performance. The research to date suggests the engine could operate in diesel – hydrogen or diesel only mode without significant degradation in BSFC or toxic emissions, facilitating the introduction of a hydrogen supply infrastructure. The flexibility in dual mode operation would ensure the vehicle operator could use the existing diesel supply network using hydrogen when available. The quantity of hydrogen stored on the truck can be sized to fit available space for the hydrogen tank, increasing as new hydrogen storage technology is developed. The vehicle range will therefore not be compromised as would be the case for a hydrogen only solution.

## 6    CONCLUSIONS


A heavy duty single cylinder engine was successfully operated on diesel – hydrogen fuel, with up to 50% of the energy contribution coming from the hydrogen fuel (equivalent to 8% concentration in the inlet manifold). A degradation in BTE of 1% was observed which was attributed to incomplete combustion of the homogenous mixture of hydrogen. The reduction in BTE was generally less than the penalty observed by other researchers and may be due to good mixing due to the high diesel injection pressures available from the F2E fuel system. Further optimisation of the combustion system such as increasing the swirl level could further reduce the BTE penalty by improving the hydrogen combustion efficiency.

$NO_x$ levels generally increased, but not excessively, and in line with the findings of other groups working on similar engines. The use of light levels of EGR achieved engine out $NO_x$ levels consistent current SCR aftertreatment systems in use to achieve Euro VI commercial vehicle emissions levels.

A review of various hydrogen supply pathways showed bulk manufactured hydrogen by either electrolysis or the steam reformation of methane would not deliver an overall $CO_2$ benefit when the primary energy supply to manufacture the hydrogen was considered. However, in the future as the carbon intensity of the electricity system decreases such an option may be attractive. In particular, the use of hydrogen as an energy buffer for absorbing wrong time low carbon energy could be particularly attractive as more renewable generation is introduced to the network. On board manufacture using steam reformation was also considered which, through the recovery of waste heat from the vehicle exhaust, would deliver an overall system benefit to improve fuel economy by potentially up to 5%.

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